Design and evaluation of a continuous flow microwave pasteurization system for apple cider

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Abstract

The purpose of this project was to design a continuous flow microwave pasteurization system and to evaluate the following process parameters: volume load size (0.5 and 1.38 l), input power (900–2000 W), and inlet temperature (3 °C, 21 °C, and 40 °C). Water and two apple ciders, one from a cold press and the other from a hot press extraction, were the fluids used to study the heating characteristics. Volumetric flow rate and absorbed power were criteria in the evaluation. The microwave pasteurization system consisted of helical coils throughout a large cavity oven, which was shown to produce uniform and reproducible heating throughout the cavity. Fluid viscosity of water and cider was measured at temperatures between 20 °C and 70 °C to characterize the flow in helical coils based on the Dean number. Process lethality was verified based on inoculation of *Escherichia coli* 25922 in apple cider, in which the pasteurization process resulted in a 5-$\log_{10}$ reduction.
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Keywords: Microwave; Pasteurization; Cider; Viscosity; Dean number

1. Introduction

Traditionally, acidic foods such as fruit juices were not recognized as vehicles for foodborne illnesses; however, there have been three pathogens (*Salmonella enterica, E. coli* O157:H7 and *Cryptosporidium parvum*) associated with foodborne illnesses in fruit juices (Besser et al., 1993; Centers for Disease Control and Prevention (CDC), 1997). Most outbreaks involving *E. coli* O157:H7 and *S. enterica* have occurred in apple and orange juice. In 1991, *E. coli* O157:H7 was confirmed as the epidemiological agent in apple juice, and it has since been suspected in earlier outbreaks involving apple cider. Since a series of outbreaks in 1996 were associated with unpasteurized fruit juices, the FDA required all fruit and vegetable juice processors to implement a HACCP plan that included a performance criterion to assure juice safety (Food and Drug Administration (FDA), 2001). Juice processors in the US must have a system that results in a 5-$\log_{10}$ reduction of the most resistant organism of public health concern (Mazzotta, 2001). The National Advisory Committee on Microbiological Criteria for Foods recommended *E. coli* 0157:H7 and *Listeria monocytogenes* (*L. monocytogenes*) be used as appropriate target organisms for fruit juices. However, there have been no reported outbreaks involving *L. monocytogenes* in fruit juices (Mazzotta, 2001).

The heat resistance of *E. coli* O157:H7 in apple cider is well known (Miller & Kaspar, 1994; Splittstoesser, McLellan, & Churey, 1996; Buchanan & Edelson, 1999). Splittstoesser et al. (1996) found the D_{52C} value of *E. coli* O157:H7 for most apple ciders was 18 ± 6.3 min with a z-value of 4.8 °C. Therefore, a thermal process consisting of 71 °C for 6 s should result in a 5-log reduction of *E. coli*. It was also concluded that a high pH (> 4.4) increased the thermal resistance of *E. coli*.

Inactivation of microorganisms and reduction of quality attributes are both highly dependent on time-temperature treatments during pasteurization, so optimization of this process is crucial in obtaining a safe and

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high-quality product. Because of the potential benefits of delivering reduced thermal exposure to inactivate pathogenic microorganisms while maintaining high quality, continuous-flow microwave pasteurization systems have created much interest in the beverage industry and thus has been investigated for various beverages, such as apple juice (Tajchakavit, Ramaswamy, & Fustier, 1998; Cañumir, Celis, de Bruijn, & Vidal, 2002), milk (Knutson, Marth, & Wagner, 1988; Kudra, Van de Voort, Raghavan, & Ramaswamy, 1991; Villamiel, López-Fandiño, Corzo, Martínez-Castro & Olano, 1996) and orange juice (Nikdel, Chen, Parish, MacKellar, & Friedrich, 1993; Tajchakavit & Ramaswamy, 1995). While many investigations on microwave pasteurization have focused on microbial (Fujikawa, Ushioda, & Kudo, 1992; Koutchma & Ramaswamy, 2000) and enzyme inactivation (Tajchakavit & Ramaswamy, 1997a, b), very little work has been conducted on evaluating process and product parameters of a continuous-flow microwave pasteurization system. Therefore, the objectives of this project were to design a lab-scale continuous flow microwave pasteurization system for apple cider and to characterize the process parameters. The following parameters were evaluated: input power, volume load size, volumetric flow rates, product viscosities, and inlet temperatures. Pasteurization of this system was evaluated by the inactivation of a surrogate *E. coli* strain (25922) inoculated in apple cider.

2. Materials and methods

2.1. Preparation of apple cider

Apples (*Malus* X *domestica* Borkh) were processed for cider according to the procedures developed for a lab-scale rack and frame press (Gerard & Roberts, 2004). Liberty, Fuji, and Macintosh varieties were used due to their availability and prevalence in cider production (Downing, 1989). The apples (1600 g batches) were milled at 1750 rpm for 40 s in a commercial food processor (Robot coupe®, model R6VN series D, Ridgeland, MS). The mash (3200 g) was then pressed in a lab-scale, three layer rack-and-frame press (Carver Laboratories model 3925, Wabash, IN). The apples were pressed at two temperatures: one was a cold press at 21 °C, and the other was a hot press at 60 °C. Gerard and Roberts (2004) have shown that hot pressing improved juice yields and total phenolic and flavonoid extraction into the cider without effecting the cider's sensory properties; therefore, pasteurization of cider produced from hot pressing was also investigated. For hot pressing, the apple mash (3200 g) was placed in a rectangular polypropylene container (0.533 m × 0.375 m × 0.081 m) at a depth of 0.016 m. The mash was heated in a 2450 MHz microwave oven at 1500 W

for 11 min to achieve a bulk temperature of 60 °C. These parameters of heating apple mash in the microwave were previously found to be optimum (Roberts & Gerard, 2004). The bulk temperature was monitored using four fiber optic probes (Luxtron Corporation, Santa Clara, CA) placed at the corner, edge, center and half-way between the corner and center (middle).

2.2. Continuous flow microwave pasteurization apparatus

Fig. 1 is a schematic of the continuous flow microwave pasteurization system. The microwave oven is powered by a 2450 MHz magnetron with continuous variable power control from 0–2,500 W (GAE Inc., Modesto, CA). The magnetron connects to the oven cavity using WR-284 waveguide components. The oven cavity measures $0.88 \times 0.88 \times 0.88 \, \text{m}^3$ and has two-mode stirrers operating at different speeds, 30 and 35 rpm. Both the cavity and the mode stirrers were made of aluminum. Input and reflected power are measured using power meters (Model 435B, Helwett Packard Corp., Santa Clara, CA) connected to a directional coupler in the waveguide. The microwave oven was designed to insure uniform heating independent of position within the cavity. To confirm this uniformity, 1 litre of water at 4 °C contained in a Teflon beaker was used to measure absorbed power (IEC, 1988) in nine locations throughout the cavity, as shown in Fig. 2. The input power was 900 W and fiber optic probes were used to monitor the time-temperature data (Luxtron, Corp, model 790, Santa Clara, CA). Two-way ANOVA analysis was used to determine if there was a significant difference ($P \leqslant 0.05$) between the absorbed power for the three levels and three positions within each level. The absorbed power for each position was measured in triplicate, so the experimental design was 9 (positions) × 3 (replicates).

For the continuous-flow system, the product was pumped into the microwave oven through a series of Teflon helical coils (Cole Parmer Instrument Co., Vernon Hills, IL) using a peristaltic pump (Masterflex®, model no. 7521-40, with EasyLoad® pump head, model no. 7518-12, Cole Parmer Instrument Co., Vernon Hills, IL). The tubing dimensions for each coil are 0.0064 m I.D. and 0.0095 m O.D. The dimensions of each coil are 0.045 m I.D., 0.063 m O.D., a relaxed length of 0.61 m, and an extended length of 5.486 m. The coils were placed onto a polycarbonate support stand (Fig. 3). The base of the stand, Part A, measures 0.610 m × 0.610 m × 0.0254 m. The stand consisted of three levels, and each level can support up to three separate coils. The coils are supported by horizontal polycarbonate cylinders, Parts D, which run through the center of the coils, as shown in Fig. 3. The D cylinders are supported by horizontal polycarbonate cylinders, Part C, which run perpendicular to D and are supported
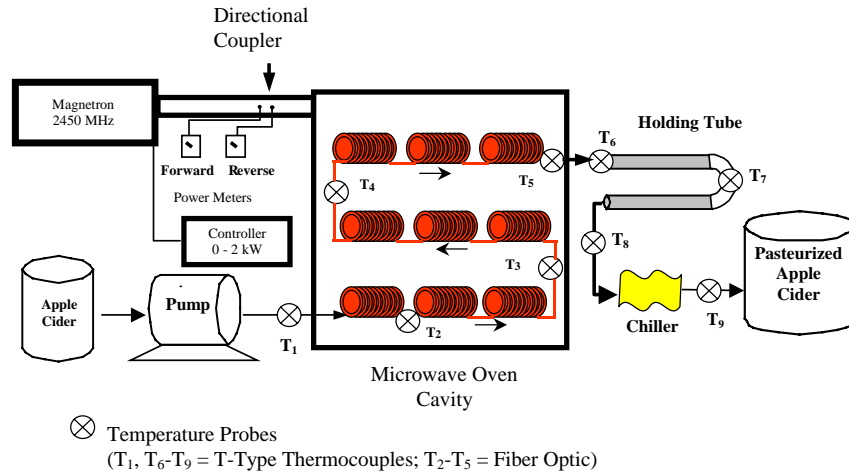
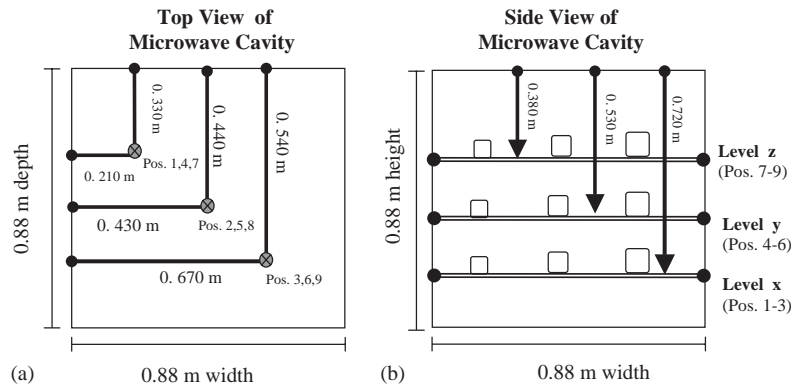Fig. 1. Continuous-flow microwave pasteurization system.

Fig. 2. Diagram of the container positions to test heating uniformity with respect to width and depth (a) and with respect to height (b).

by vertical polycarbonate cylinders, Part B. Upon exiting the microwave oven, the product was then passed through insulated holding tubes before being cooled with a tube-in-tube heat exchanger (Exergy Inc., Hanson, MA). Thermocouples (Type T) were placed at the entrance and exit of the microwave cavity, and after the chiller. In addition, fiber optic probes monitored the temperature within the cavity, as shown by temperature probes $T_2 - T_5$ in Fig. 1. The thermocouples were connected to a data acquisition system (OMB DAQ-56, Omega Engineering Inc, Stamford, CT) that recorded data every 3 s, while the Luxtron system collected temperature data from the fiber optic probes every second. All of the temperature probes were calibrated using ice water slurry (0 °C) and boiling water (100 °C).

The volumetric flow rates were determined for various pump settings. For the pasteurization system, the flow rates were adjusted until the fluid exiting the cavity was 73 °C. This slightly higher target temperature counters some heat loss the fluid may experience exiting the system and insures that the fluid maintains a tempera-

ture above 71 °C throughout the holding tubes. Food dyes were used to determine both transit time and resident times within the cavity. The times were measured in triplicate through each coil, between coils and throughout the system. In addition, the time to collect 0.25, 0.5 and 1 l samples were used to measure the volumetric flow rate. The volumetric flow rates were measured in triplicate for each pump setting and for each fluid (cider and water). From the transit-time and temperature measurements, time-temperature profiles were generated.

Absorbed power can be calculated calorimetrically using Eq. (1) (Gerling, 1987)

$$P_{abs} = V \rho C_p \left[\frac{\Delta T}{\Delta t} \right], \tag{1}$$

where P_{abs} is the absorbed power (W), V is the volume and is the load capacity within the cavity (l), ρ is the density of the fluid (kg/m^3), C_p is the specific heat capacity (J/kg°C), and $\Delta T / \Delta t$ is the heating rate (°C/s). Since significant heat loss occurs above 40 °C and would compromise the heating rate measurements, the power
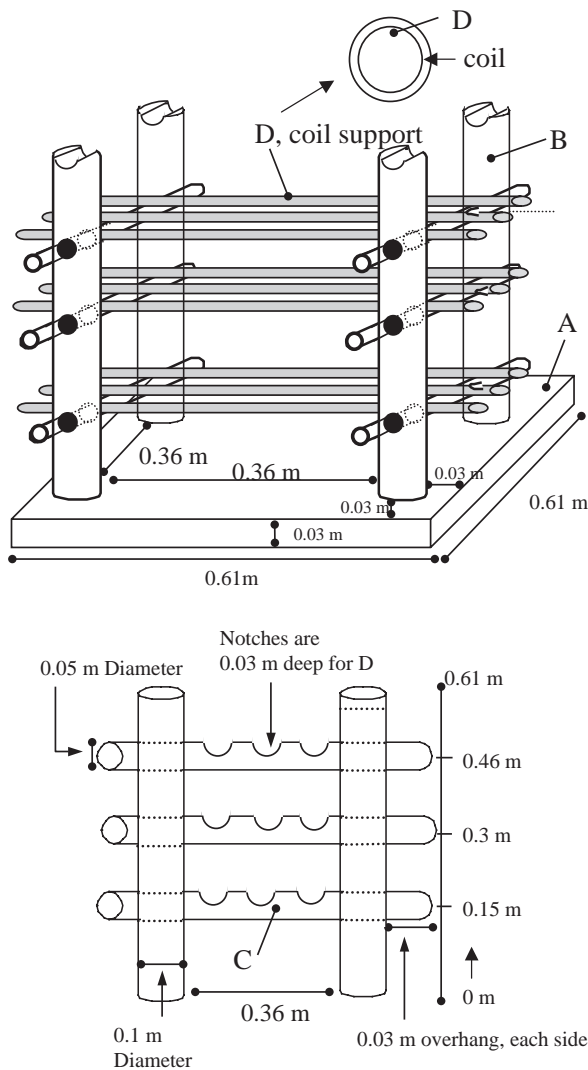
Fig. 3. Polycarbonate support stand for helical coils within the microwave cavity.

absorption was measured from heating rates between the inlet temperature and 30 °C. The density of water was taken as 1000 kg/m^3, and the density of cider experimentally determined using a hand hydrometer (HB Instruments, Collegeville, PA) was 1040 kg/m^3. The specific heat capacity for water was 4182 J/kg°C, and the specific heat capacity for cider was calculated using the Dickerson model for fruit juices (Heldman & Singh, 1981)

$$C_p(kJ/kg\,°C) = 1.675 + 0.025M, \tag{2}$$

where M is the moisture content (g/100 g). The cold-pressed cider had a soluble solid content of 12 g/100 g and the hot-pressed cider had a soluble solid content of 13 g/100 g, so the specific heat capacities for cold- and hot-pressed cider were 3875 J/kg°C and 3850 J/kg°C, respectively.

The input power is not completely absorbed into a food material. Some power is reflected back towards the magnetron and some is lost to the cavity. Therefore, the net available power can be calculated as follows:

$$P_A = P_I - P_R - P_C \tag{3}$$

where P_A is the net available power delivered to the fluid (W), P_I is the input power (W), P_R is the reflected power (W), and P_C is the power lost to the cavity. The input and reflected powers are measured using the power meters. The power lost to the cavity was determined by a modified form of Eq. (3), where net available power, P_A, was replaced by absorbed power calculated using Eq. (1). A cavity made of aluminum can absorb up to 10% of the input power (Gerling, 2002).

2.3. System parameters

The microwave pasteurization apparatus was evaluated based on the load size, input power, and inlet temperature. Fluid viscosity was also measured to characterize the flow through the system. Optimum volumetric flow rates and power absorption were the criteria in analysing these process parameters.

Load size: Two pasteurization load-size configurations were analysed. The first consisted of three helical coils, one on each level of the support stand, with a total volume of 0.5 l within the cavity. The second configuration consisted of nine coils, three on each level, with a total volume of 1.38 l within the cavity. Water was run through each configuration using 2000 W input power and at flow rates that resulted in an outlet temperature of 73 °C. Time-temperature profiles were obtained and power absorption was calculated using Eq. (1). Four replicates were conducted on each configuration, so the experimental design was 2 (load-size configurations) $\times$ 4 (replicates).

Input power: Water was pumped through the pasteurization system (1.38 l capacity) at a constant flow rate (0.38 l/min) and 21 °C inlet temperature. The heating rates were measured and the absorbed power calculated from the following input power settings: 900 $\pm$ 60, 1200 $\pm$ 60, 1500 $\pm$ 60, 1800 $\pm$ 60, and 2000 $\pm$ 60 W. The experiments were conducted in triplicate, so the experimental design was 5 (power settings) $\times$ 3 (replicates).

Effects of fluid and inlet temperature: The cider produced from mash at 60 °C had the highest quality and yields, and the corresponding cider temperature was 43.2 $\pm$ 1.7 °C. Based on these results, the microwave pasteurization system performance was analysed for water, cold- and hot-pressed cider with inlet temperatures of 20 °C, as well as cider samples with inlet temperatures of 3 °C, 22 °C, and 40 °C.

Fluid characteristics: Thermal processes require the coldest point to experience a minimal pasteurization temperature for a specified length of time. The cold

point in a continuous-flow process is the region where fluids are at maximum velocity, which is the axial position in a straight tube. The maximum velocity can vary in a helical coil; therefore, the flow characteristics needed to be determined. The use of helical coils creates a secondary flow due to the momentum transfer in the radial direction, which ensures proper mixing and stabilizes laminar flow (Sandeep & Puri, 2001). The Dean number (*De*) quantifies this phenomenon and therefore is the dimensionless parameter to characterize flow in helical coils (Sandeep & Puri, 2001)

$$De = Re\sqrt{\frac{D_{\text{tube}}}{D_{\text{coil}}}}, \tag{4}$$

where D_{tube} is the inside diameter of the tube (0.0064 m), D_{coil} is the diameter of the coil (0.045 m), and *Re* is the Reynolds number (dimensionless) and can be calculated based on volumetric flow rate, $\dot{V}(\text{m}^3/\text{s})$, as follows:

$$Re = \frac{\rho(\dot{V}/A_x)D_{\text{tube}}}{\eta}, \tag{5}$$

where ρ is the density of the fluid (kg/m³), A_x is the cross-sectional area of the tube (3.22×10^{-5} m²), and η is the viscosity of the fluid (kg/m s). The viscosities for each sample (water, cold- hot-pressed cider) were evaluated at 20°C, 25°C, 30°C, 40°C, 45°C, 50°C, 60°C, and 70°C using a Cannon Fenske glass capillary viscometer (Cannon Instrument Co., State College, PA). Measurements were conducted in triplicate, so the experimental design was 3 (fluids) × 8 (temperatures) × 3 (*replicates*).

2.4. System evaluation

2.4.1. Microbial inactivation

The microbial inactivation of *E. coli* 25922 was evaluated using 2000 W. A 7-l volume of apple cider (Fuji) was inoculated with 80 ml of an *E. coli* 25922 culture (Dr. Randy Worobo, Cornell University, Geneva, NY). The apple cider (Fuji), which had a pH of 4.1, was pasteurized at 71°C for 6 s (FDA, 2001) using the continuous-flow microwave pasteurization system at 2000 W. Two methods were used for enumerating *E. coli* 25922 in apple cider before and after pasteurization: pour plate method and Petrifilm® (*E. coli*/Coliform count plate, 3 M, St. Paul, MN). The same dilution scheme was used for both methods using peptone water (Difco Laboratories, Detroit, MI). For the pour plate method, 1 ml aliquots were added to a layer of violet red bile agar (Difco Laboratories, Detroit, MI) on petri dishes (Fischer Scientific, Pittsburgh, PA), an overlay of violet red bile agar was then applied. Finally, the plates were incubated at 37 ± 2°C for 48 h (Kornacki & Johnson, 2001, Chapter 8). The Petrifilm®s were incubated at 35 ± 2°C for 48 ± 2 h based on the AOAC

official method 991.14 (AOAC, 1998). The results were expressed as cfu/ml of cider. The inoculation study was performed in triplicate and each sample was plated in duplicate.

2.4.2. Efficiency and scale-up

Knowing the energy requirements to heat a food, the rate at which energy is absorbed, and the heat loss during the process, a microwave heating system can be evaluated and optimized. Eq. (6) calculates the energy required to heat a specific product volume

$$Q(\text{J}) = mC_p\Delta T = V\rho C_p\Delta T. \tag{6}$$

Eqs. (1) and (2) determine the rate of power absorbed with respect to the net available power delivered to the system. Eq. (7) calculates the convective heat loss from each coil, *q*

$$q_{\text{convection}} = h_{\text{air}}A_s(T_\infty - T_s), \tag{7}$$

where h_{air} is the convective heat transfer coefficient for free convective air (10 W/m²°C), A_s is the surface area for the coil (m²), T_s is the surface temperature of the coil (°C), and T_∞ is the air temperature within the microwave cavity (°C). The surface area of a coil was calculated using the following equation

$$A_s = L_T C_T = L_T(\pi D_T) = 49.37\,\text{m}(\pi 0.0095\,\text{m}) = 1.47\,\text{m}^2, \tag{8}$$

where L_T is the total length of the extended coils (m), C_T is the circumference of the tube (m), and D_T is the diameter of the tube (m). Accounting for the heat lost from the system using Eq. (7), the net power absorption, P_{netabs}, can be determined

$$P_{\text{net abs}} = P_{\text{abs}} - P_{\text{lost}}. \tag{9}$$

Eq. (1) can also calculate the net power absorption using the heating rates measured from the fluid's temperature entering the cavity at $t = 0$ s and the fluid's temperature exiting the cavity at the residence time. Finally, from the energy requirement for a given inlet temperature, load volume and net power absorption, the following equation calculates the volumetric flow rate:

$$\dot{V}(\text{l/min}) = \frac{V\,(\text{l})P_{\text{net abs}}(\text{W})}{Q_{\text{Ti}}(\text{J})}\left(\frac{60\,\text{s}}{\text{min}}\right). \tag{10}$$

Eq. (10) can also be used to estimate the volumetric flow rate of a scaled-up microwave pasteurization system with the same helical coil dimensions. The net absorbed power is critical for this calculation, but the heating characteristics from the current pasteurization system as well as any improvements will be assumed when determining the volumetric flow rates of a larger system.

3. Results and discussion

3.1. Continuous flow microwave pasteurization apparatus

The average heating rate from the IEC power tests was $0.14 \pm 0.005\,°C/s$ and the average absorbed power was $603 \pm 20\,W$ for $1\,l$ of water placed at nine different locations within the microwave cavity, as shown in Fig. 4. The results showed that there were no significant difference ($P \leqslant 0.05$) in absorbed power with respect to levels and position within the microwave cavity. This power uniformity confirms the uniform electric field measurements on this oven in a previous study (Rizvi, Goedeken, Steet, & Tong, 1994). Much of this uniform and reproducible heating is a result of the large cavity size (Lentz & Anderson, 1979; D'ambrosio, Di Meglio, & Ferrara, 1980), and therefore this microwave oven is ideal for studying heat processes on a small scale to then better simulate large-scale microwave processing.

3.2. System parameters

3.2.1. Load size

The continuous flow microwave pasteurization system was compared at two different load volumes using $2000\,W$. The flow rate for the $0.5\,l$ system needed to be as low as $0.23\,l/min$ to achieve a resident time of $130\,s$ necessary to heat the cider to $73\,°C$. To improve the flow rate, the second design had nine coils resulting in a total volume of $1.38\,l$ within the microwave cavity and the flow rate increased to $0.38\,l/min$. The resident time also increased from 130 to $216\,s$. Using Eq. (1), the power absorbed for water in the $0.5\,l$ system was only $898\,W$ with a power input of $2000\,W$. For the $1.38\,l$ system, the water absorbed $1789\,W$. This shows that the larger capacity system is more efficient and suggests the load volume is either at or approaching its maximum absorption capacity. Using the smaller volume, one can calculate the energy absorption density (q/V) for

Fig. 4. Absorbed power within the microwave cavity.

water (Toledo, 1999)

$$q/V(W/cm^3) = \frac{P_{abs}(W)}{V(l)}\left(\frac{1\,l}{1000\,cm^3}\right)$$
$$= \frac{897.7(W)}{0.500(l)}\left(\frac{1\,l}{1000\,cm^3}\right) = 1.8\,(W/cm^3).$$

$$(11)$$

Given the absorbed power ($1789\,W$) for the $1.38\,l$ system and using Eq. (11), the optimal volume for this particular microwave cavity at $2000\,W$ is

$$V_{opt}(l) = \frac{P_{abs}(W)}{q/V(W/cm^3)}\left(\frac{1\,l}{1000\,cm^3}\right)$$
$$= \frac{1789(W)}{1.8(W/cm^3)}\left(\frac{1\,l}{1000\,cm^3}\right) = 0.99\,l$$

$$(12)$$

Thus, any volume greater that $1\,l$ in this microwave oven will heat at the rate determined by the input power of the oven.

3.2.2. Input power

Table 1 shows the heating rates and absorbed power of the water at each input power. The advantage of this particular microwave apparatus is that it has the capability of delivering continuous variable power, unlike most lab-scale microwave ovens that duty-cycle the power on and off when set below maximum output. The available power was also provided for each input power setting, which takes into consideration the reflected power and power lost to the cavity, as shown in Eq. (3). The reflected powers using this $1.38\,l$ system for water are: $50\,W$ for an input power of $900\,W$, $70\,W$ for input power of 1200 and $1500\,W$, and $100\,W$ for input powers of 1800 and $2000\,W$. The power lost to the cavity is $50\,W$. Table 1 also shows the absorbed power to input power ratio as well as the absorbed power to available power ratio. For all input power experiments, the ratios of the absorbed power to the available power are high, > 0.84, with $2000\,W$ input power being the highest with 0.95. The heating rate was also the greatest using $2000\,W$. The time for the water to heat to a given temperature using $900\,W$ was over 2.5 times more than the time using $2000\,W$. Thus, operating the pasteurizer at power levels lower than $2000\,W$ would result in a significant decrease in the flow rate in order to increase the resident times necessary for water to reach pasteurization temperature. To maximize the flow rates and efficiency, $2000\,W$ was used in the remaining evaluations.

3.2.3. Effects of fluid and inlet temperature

Fig. 5 shows the temperature profiles for water, cold- and hot-pressed cider. The fluids had very similar flow rates, with hot-pressed cider having a slightly greater flow rate of $0.39\,l/min$, followed by water with $0.38\,l/min$ and cold-pressed cider with $0.36\,l/min$. The hot- and
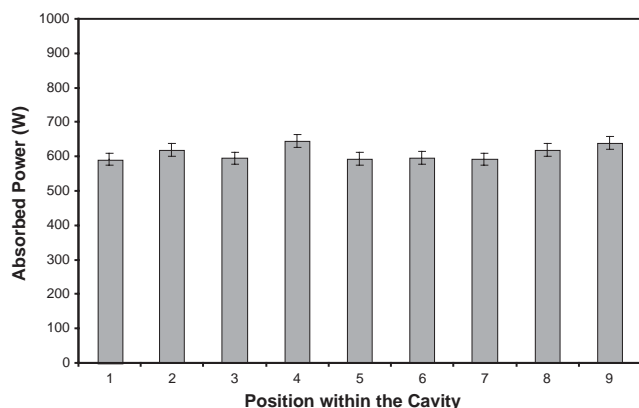
Table 1
Power absorption comparison on water being heated using various input powers in the 1.381 capacity microwave pasteurization system with a constant flow rate of 0.391 l/min and inlet temperature of 21°C

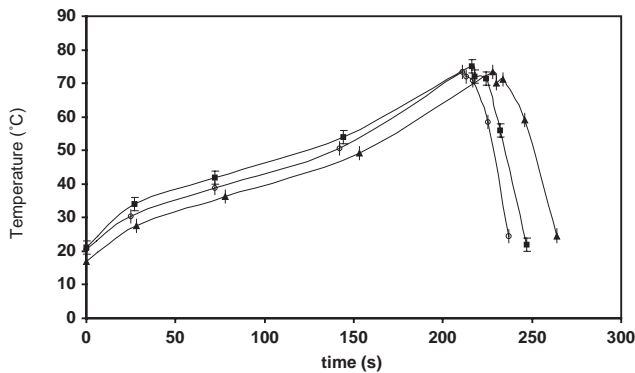| Input power, P_I (W)	Available power, P_A (W)	Heating rate $T_1 - T_3$ (°C/s)	Absorbed power, P_{abs} (W)	P_{abs}/P_I	P_{abs}/P_A
900 ± 60	800	0.12	694.7	0.77	0.87
1200 ± 60	1080	0.15	908.4	0.76	0.84
1500 ± 60	1380	0.20	1154.2	0.77	0.84
1800 ± 60	1650	0.26	1500.5	0.83	0.89
2000 ± 60	1850	0.31	1789.1	0.89	0.95

Fig. 5. Time-temperature profiles for microwave pasteurization using 2000 W with flow rates optimized for water (—■—), hot-pressed cider (—○—), and cold-pressed cider (—▲—) with an inlet temperature of 20°C.
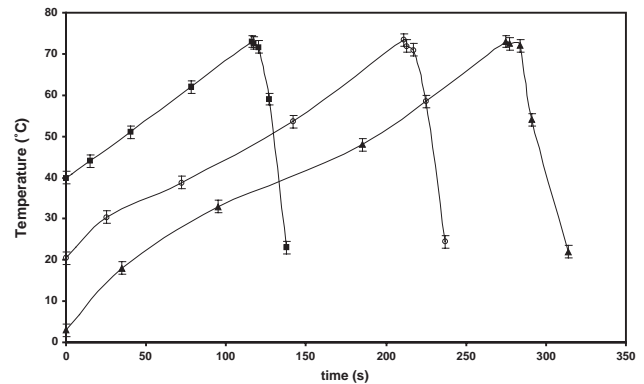

Fig. 6. Time-temperature profiles for microwave pasteurization of hot-pressed cider using 2000 W with flow rates optimized for inlet temperatures of 3°C (—▲—), 21°C (—○—) and 40°C (—■—).

cold-pressed cider had parallel profiles at the beginning of the process while water had the greatest heating rate initially. All three fluids had similar heating rates between 30°C and 50°C, but above 50°C the hot-pressed cider had a slightly greater heating rate while the cold-pressed cider and water continued to have similar heating rates to the end of the process. Since hot-pressed and cold-pressed ciders only differ in soluble solids by 1 g/100 g, the dielectric properties of these two fluids are assumed to be similar. Therefore, the slightly enhanced heating rate of the hot-pressed cider may be due to the differences in fluid viscosity. Fig. 6 shows the time-temperature profiles for hot-pressed cider at three different inlet temperatures (3°C, 22°C, 40°C) pasteurized using 2000 W with flow rates of 0.3, 0.39, and 0.71 l/min, respectively. The inlet temperature had a significant effect ($P \leqslant 0.05$) on the flow rates of the fluid, with the 40°C inlet temperature having almost double the flow rate of the 21°C inlet temperature. However, the initial heating rate was greater for the cider entering at 3°C followed by the cider entering at 21°C, and the cider entering at 40°C had the lowest heating rate. This may be explained by the fact that dielectric properties, particularly dielectric loss, for food materials without salt are greatest at temperatures just above the melting point (Datta, 1990). Even with lower heating rates, the cider with the higher inlet temperature had a much greater flow rate due to the lower heating requirement.

3.2.4. Fluid characteristics

Fig. 7a shows the viscosity of the different samples (water, cold- and hot-pressed cider) versus temperature. The viscosities are higher for apple cider samples than water, with the hot-pressed cider having a much higher viscosity than the cold-pressed cider between 20°C and 50°C. The correlation between viscosity and temperature can be described by the Arrhenius relationship:

$$\eta_a = \eta_{\infty A} \exp(E_a/RT), \tag{13}$$

where η_a is the apparent viscosity (cP), $\eta_{\infty A}$ is the frequency factor (cP), E_a is the activation energy (kJ/mol), R is the gas constant (8.317×10^{-3} kJ/mol K), and T is the temperature (K). Fig. 7b shows the Arrhenius relationship between viscosity and temperature. The activation energies for hot-, cold-pressed cider and water were 21.3, 15.5, and 13.0 kJ/mol, respectively. The viscosity and activation energy of water and cold-pressed cider were within reported values (Saravacos, 1970; Denn, 1980). However, the activation energy for hot-pressed cider was greater than for cold-pressed cider, which indicates the viscosity of hot-pressed cider is effected more by temperature. This difference in both viscosity and activation energy is related to the composition of the ciders, where hot pressing of apple mash would increase the pectins and protein concentrations extracted into the juice. Physicochemical
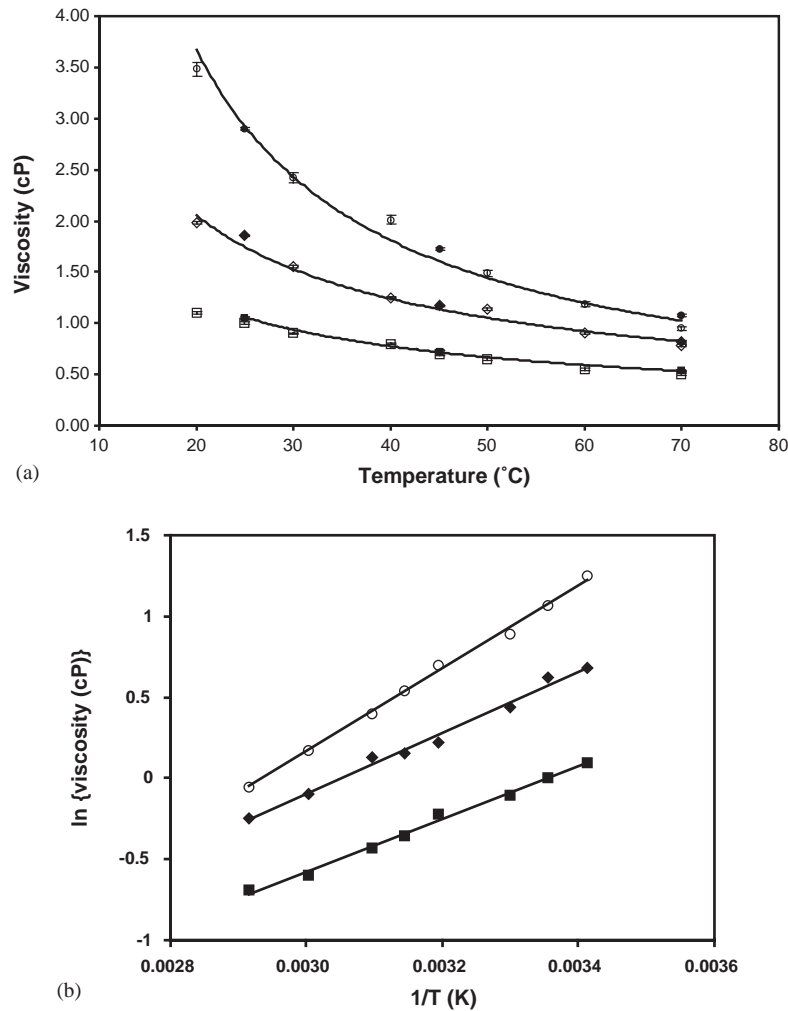
Fig. 7. The effect of temperature on viscosity: (a) viscosity-temperature profiles for unpasteurized cold-pressed cider (—◇—), pasteurized cold-pressed cider (—◆—), unpasteurized hot-pressed cider (—⊖—), pasteurized hot-pressed cider (—●—), measured water (—■—), water data from Denn (1980) (—▢—); (b) Arrhenius plot of viscosity for hot-pressed cider (—⊖—), cold-pressed cider (—◆—), and water (—■—).

evaluation of the hot-pressed cider showed increased soluble solids and turbidity with increasing press temperature (Gerard & Roberts, 2004).

Table 2 lists the Reynolds numbers and Dean numbers for water and the ciders being processed in the continuous microwave pasteurization system. The calculated *Re* numbers indicates laminar flow, which would indicate a parabolic profile for the fluids being pumped through a straight tube. However, the use of helical coils creates secondary flow perpendicular to the main direction of flow due to the centrifugal force exerted by the curvature of the coil, and this secondary flow results in the maximum velocity being pushed outward from the center (Palazoglu & Sandeep, 2002a). The Dean number quantifies this secondary flow. Table 2 shows that the Dean numbers are all above 100, which are considered high Dean numbers (Dravid, Smith, Merrill, & Brian, 1971). Prediction of velocity profiles of laminar flow in helically coiled pipes having

Table 2
Fluid properties of water, cold-pressed (CP) cider, and hot-pressed (HP) cider for continuous microwave pasteurization system

Fluid	*Re* (20–70°C)	*De* (20–70°C)
Water	1182–2364	446–892
CP-cider	653–1552	246–585
HP-cider	464–708	175–267

Dean numbers ranging within those in Table 2 showed profiles resembling plug flow (Patankar, Pratap, & Spalding, 1974). Such a velocity profile is ideal for heating liquids in a microwave oven where the fluid particles with maximum velocity span across most of the tube.

Palazoglu and Sandeep (2002b) conducted simulations of Newtonian fluids in laminar flow with Dean numbers ranging $44 \leqslant De \leqslant 287$ to study the effect of various process parameters on the fluid flow in helical

coils. The greater the Dean number the more narrow the residence time distribution (RTD) of the flow; however, the influence of RTD with Dean number is not a linear relationship. Their results showed that a given increase in Dean number when the Dean numbers were low had a more significant reduction in the RTD than for a similar increase in Dean number when the Dean numbers were high. Thus, the effect of increasing Dean number resembled an exponential decrease on the RTD. The high viscosity of hot-pressed cider at 20 °C results in a much lower Dean number as the cider enters the pasteurizer than for water and cold-pressed cider. This low Dean value due to high viscosity may indicate weaker Dean vortices (Kluge, Kalra, & Belfort, 1999) As the hot-pressed cider heats, its viscosity reduces as shown in Fig. 7a, and its Dean number increases thus increasing the effect of the secondary flow and mixing. The Dean numbers for water and cold-pressed cider are much higher than the hot-pressed between 20 °C and 70 °C. Therefore, the significant decrease in viscosity for hot-pressed cider between 20 °C and 40 °C increases the Dean number such that it may have a larger effect in mixing and reducing the RTD than for water and cold-pressed cider. The improved mixing and reduction of RTD could explain why the hot-pressed cider has a greater heating rate in the latter stages of pasteurization. This conclusion is supported by the constant heating rate of the hot-pressed cider entering the pasteurizer at 40 °C, as shown in Fig. 6. The steady heating rate throughout the pasteurization may be due to the fact that the hot-pressed cider is entering the system at a Dean number where any further increase would not significantly improve the mixing.

3.3. System evaluation

3.3.1. Microbial inactivation

Using the time-temperature profile and the microbial-inactivation kinetics for *E. coli*, Eq. (14) calculates the lethal rate, L, for a given time interval

$$L = 10^{(T-T_r)/z}, \tag{14}$$

where z is the thermal resistance (°C), T is the process temperature at time t (°C), and T_r is the reference temperature (°C). Fig. 8a shows both the temperature profile of cold-pressed apple cider pasteurized in the microwave using 2000 W at a flow rate of 0.36 l/min and the calculated lethality curve for a z-value of 6.0 °C and 80 °C reference temperature. Based on the lethality curve, the total lethality for a specific microorganism can be determined

$$F_0 = \int_0^t L \, dt, \tag{15}$$

where t is the time at a target process temperature. Eq. (16) calculates the reduction in a specific microbial population

$$\log_{10}\left[\frac{N_0}{N}\right] = \frac{F}{D}, \tag{16}$$

where N_0 is the initial microbial population and D is the time a microorganism will reduce by 1-log cycle at a specific temperature. For the pasteurization of apple cider shown in Fig. 8a, the total lethality, F_{80C}, achieved in the process was 3.9. So given a D_{80C} value of 0.755 s, the reduction of *E. coli* 25922 would be

$$\log_{10}\left[\frac{N}{N_0}\right] = \frac{3.9(s)}{0.76(s)} = 5.13.$$

Fig. 8b shows the actual reduction of *E. coli* 25922 from the inoculation experiments. There was a $5.2 \pm 0.10 \log_{10}$ reduction in *E. coli* in all three-inoculation studies, which correlates with calculated reduction from the time-temperature plot. Therefore, the optimized pasteurization system achieved expected inactivation of the target organism.

3.3.2. Efficiency and scale-up

The time-temperature profiles shown in Fig. 5 also indicate a few unique heating characteristics. The water did initially heat faster than either the hot-pressed cider or the cold-pressed cider, which resulted in greater absorption of power shown in Table 3. The heating rates between the hot- and cold-pressed cider were similar initially, as shown by similar power absorption. As the fluid temperature increases, there is increased convective heat loss to the ambient air. The temperature profiles in Fig. 5 show that the temperatures at each probe location has minimal flucuation, thus it can be assumed that the rate of energy absorption by the fluid is in equilibrium with the rate of energy lost to the air in the cavity. Assuming the surface temperature of the Teflon tubing is equal to the fluid temperature throughout the cavity, the heat loss was calculated for every 2 s using Eq. (7) and the time-temperature profile. The Simpson's Rule was used to determine the total heat loss. Table 3 shows the absorbed power, calculated heat loss, and the net absorbed power determined both by Eq. (1) using the difference of the outlet and inlet temperature with respect to residence time and by Eq. (9). The difference between the two methods of determining the net power absorbed was minimal. Also, the absorbed power for the cider with 40 °C inlet temperature was not able to be determined using Eq. (1) since the immediate heat loss due to the high-inlet temperature would compromise the calculation. Therefore, Eq. (9) was used to estimate the absorbed power from adding the calculated heat loss to the calculated net absorbed power. The calculated total heat loss for all heating experiments were up to 20% of the available power into the system, which suggests insulating the coils may significantly shorten the
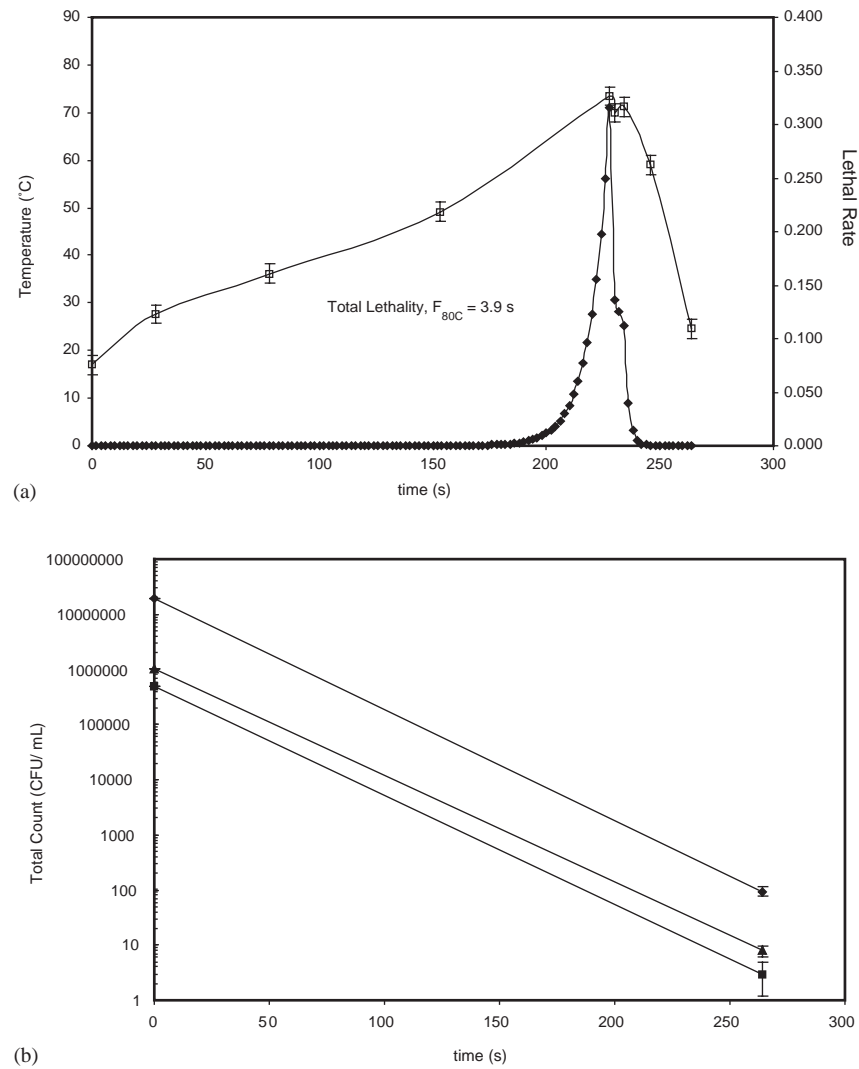
(a)

(b)

Fig. 8. (a) Temperature profile (—□—) and corresponding lethality plot (—◆—) for the pasteurization of cold-pressed cider inoculated with *E. coli* 25922 having a *z*-value of 6°C and a D_{80C} of 0.76 s; (b) Microbial inactivation of *E. coli* 25922 for inoculated apple cider processed in the microwave pasteurization system.

Table 3
Evaluation of absorbed power, heat loss and net absorbed power of 2000 W pasteurization system for water, cold-pressed (CP) cider, and hot-pressed (HP) cider

Fluid	Absorbed power[a] (W)	Heat loss (W)[b]	Net power absorbed[c] (W)	Net power absorbed[d] (W)	Difference[e]
Water ($T_i = 21°C$)	1789	383	1477	1406	0.05
CP-cider ($T_i = 17°C$)	1740	362	1377	1378	0.0
HP-cider ($T_I = 20°C$)	1719	347	1388	1372	0.01
HP-cider ($T_I = 40°C$)	1834[d]	294	1540	—	—
HP-cider ($T_I = 3°C$)	1745	320	1406	1425	0.01

[a] Eq. (1), using heating rates below 40°C.
[b] Eq. (7).
[c] Eq. (1), using inlet and outlet temperature and corresponding residence time.
[d] Eq. (9).
[e] Absolute difference between net power absorbed using Eq. (9) to net power absorbed using Eq. (1) divided by the net power absorbed using Eq. (1).

Table 4
Predicted volumetric flow rates for the pasteurization system using 2000 W for water, cold-pressed (CP) cider, and hot-pressed (HP) cider

Fluid	Energy required[a] (J)	Net power absorbed[b] (W)	Predicted volumetric flow rate[c] (l/min)	Measured volumetric flow rate (l/min)	Difference[d]
Water ($T_i = 21$°C)	323,185	1477	0.378	0.38 ± 02	0.01
CP-cider ($T_i = 17$°C)	313,941	1377	0.363	0.36 ± 02	0.01
HP-cider ($T_i = 20$°C)	292,853	1388	0.392	0.39 ± 02	0.01
HP-cider ($T_i = 3$°C)	386,786	1406	0.301	0.30 ± 02	0.0
HP-cider ($T_i = 40$°C)	182,342	1540	0.699	0.71 ± 02	0.02

[a] Eq. (6).
[b] Eq. (1).
[c] Eq. (10).
[d] Absolute difference between the predicted and measured volumetric flow rates divided by the measured flow rate.

necessary resident time and result in a more efficient system.

Table 4 shows the energy requirement, the net power absorbed, and the predicted volumetric flow rate for water, cold-and hot-pressed cider. The volumetric flow rate equation is accurate because the net power absorption accounted for the heat loss from the system. If the coils were insulated to minimize heat loss, then the net power absorption would be close to 1800 W. With this high-net power absorption, the volumetric flow rates for cider would improve to 0.51 l/min for an inlet temperature of 20°C and 0.82 l/min for an inlet temperature of 40°C. For a commercial-scale microwave tunnel with input power of 6000 W, the net available power would be 5400 W (Gerling, 2002). Using Eq. (12) based on water, the optimum volume capacity in this commercial-scale system would be 2.7 l. Using Eq. (6), the energy requirement to heat 2.7 l of cider is 576,693 J with an inlet temperature of 20°C and 359,073 J for an inlet temperature of 40°C. So with minimal heat loss from the coils and 20°C inlet temperature, the predicted flow rate would be 1.5 l/min. For a hot pressing operation in which the cider would have a 40°C inlet temperature, the flow rate would be 2.5 l/min. In a recent study comparing flash pasteurization (71°C for 6 s) to hot-fill-hold pasteurization (63°C for 1.8 min) to UV irradiation (14 mJ/cm^2) on apple cider, the results showed that there were no significant differences among the pasteurization treatments of ciders with respect to taste and preference (Tandon, Worobo, Churey, & Padilla-Zakour, 2003). In fact, the hot-fill-hold process resulted in a longer shelf-life. If a hot-fill-hold design were used for microwave pasteurization, the lower heat requirement would decrease the residence time requirement and thus increase the flow rate. Thus, for cider entering the microwave pasteurizer used in this study at 20°C and assuming 1800 W net absorbed power, the flow rate of the hot-fill would be 0.62 l/min. For 5400 W net absorbed power and 20°C inlet temperature, the

flow rate for the hot-fill would be 1.87 l/min. Furthermore, if a hot-pressed process were utilized, the hot-fill pasteurization throughput would be even greater at 3.52 l/min.

4. Conclusion

Given the physical design of the system, volume capacity and volumetric flow rates, the application of microwave energy for the pasteurization of apple cider is a feasible thermal process, especially with increased power. One major factor in designing a continuous-flow microwave pasteurization system is to insure the fluid is obtaining uniform thermal energy. The large cavity oven showed to produce uniform heating throughout the cavity and the use of helical coils would narrow the residence time distribution as indicated by the large Dean numbers. A significant improvement on the efficiency of the process would be to insulate the coils within the cavity. Research is currently underway to resolve this problem.

Acknowledgements

References

AOAC. (1998). Microbiological methods. In: P. Cunniff (Ed.), *Official Methods of Analysis of AOAC International* (16th Ed., 4th revision). (p. 13). Gaithersburg, MD: AOAC International.

Besser, R. E., Lett, S. M., Weber, J. T., Doyle, M. P., Barrett, T. J., Wells, J. G., & Griffin, P. M. (1993). An outbreak of diarrhea and hemolytic uremic syndrome from *E. coli* O157:H7 in fresh pressed apple cider. *Journal of the American Medical Association*, 269, 2217–2220.

Buchanan, R. L., & Edelson, S. G. (1999). Effect of pH-depedent, stationary phase acid resistance on the thermal tolerance of *E. coli* O157:H7. *Food Microbiology, 16*, 447–458.

Cañumir, J. A., Celis, J. E., de Bruijn, J., & Vidal, L. V. (2002). Pasteurization of apple juice by using microwaves. *Lebensmittel-Wissenschaft und-Technologie, 35*, 389–392.

Centers for Disease Control and Prevention (CDC). (1997). Outbreaks of *E. coli* O157:H7 infection and cryptosporidiosis associated with drinking unpasteurized apple juice–Connecticut and New York. *Morbidity and Mortality Weekly Report, 46*, 6–8.

Datta, A. K. (1990). Heat and mass transfer in the microwave processing of food. *Chemical Engineering Progress, 86*, 47–53.

D'ambrosio, G., Di Meglio, F., & Ferrara, G. (1980). Multimode time-varying enclosures for exposure and dosimetry in bioelectromagnetic experiments. *Alta Frequenza, 49*, 89–94.

Denn, M. M. (Ed.) (1980). *Process fluid mechanics.* Englewood Cliffs, NJ: Prentice-Hall.

Downing, D. (Ed.) (1989). *Processed apple products.* New York: Van Nostrad, Reinhold.

Dravid, A. N., Smith, K. A., Merrill, E. W., & Brian, P. L. T. (1971). Effect of secondary fluid motion on laminar flow heat transfer in helically coiled tubes. *American Institute of Chemical Engineers Journal, 17*, 1114–1122.

Food and Drug Administration (FDA). (2001). Hazard analysis and critical control point (HACCP): Procedures for the safe and sanitary processing and importing of juice; final rule. *Federal Register, 66*, 6137–6202.

Fujikawa, H., Ushioda, H., & Kudo, Y. (1992). Kinetics of *E. coli* destruction by microwave irradiation. *Applied and Environmental Microbiology, 58*, 920–924.

Gerard, K. A., & Roberts, J. S. (2004). Microwave heating of apple mash to improve juice yield and quality. *Lebensmittel-Wissenschaft und-Technologie, 37*, 551–557.

Gerling, J. E. (1987). Microwave oven power: A technical review. *Journal of Microwave Power and Electromagnetic Energy, 22*, 199–211.

Gerling, J. F. (2002). *Personal communication.* Modesto, CA: Gerling Applied Engineering, Inc.

Heldman, D. R., & Singh, R. P.(Eds.) (1981). *Food process engineering.* (2nd Ed.). New York: Van Nostrand Reinhold.

IEC. (1988). *Methods for measuring the performance of microwave ovens for household and similar purposes,* CEI IEC 705. (2nd ed.). Geneva, Switzerland: Bureau Central de la Commission Electrotechnique Internationale.

Kluge, T., Kalra, A., & Belfort, G. (1999). Viscosity effects on dean vortex membrane microfiltration. *American Institute of Chemical Engineers Journal, 45*, 1913–1926.

Knutson, K. M., Marth, E. H., & Wagner, M. K. (1988). Use of microwave ovens to pasteurize milk. *Journal of Food Protection, 51*, 715–719.

Kornacki, J. L., Johnson, J. L. (2001). Enterobacteriaceae, coliforms, and *E. coli* as quality and safety indicators. In: F. P. Downes, K. Ito (Eds.), *Compendium of methods for the microbiological examination of foods,* (4th ed.), (pp. 69–83). Washington DC: American Public Health Association.

Koutchma, T., & Ramaswamy, H. S. (2000). Combined effects of microwave heating and hydrogen peroxide on the destruction of *E. coli. Lebensmittel-Wissenschaft und-Technologie, 30*, 30–36.

Kudra, T., Van de Voort, R. F., Raghavan, G. S. V.,Ramaswamy, H. S. (1991). Heating characteristics of milk constituents in a microwave pasteurization system. Journal of Food Science, 56, 931–934, 937.

Lentz, R. R., & Anderson, H. C. (1979). *Reverberating chambers for emc measurements.* Minneapolis: Litton Microwave Cooking.

Mazzotta, A. S. (2001). Thermal inactivation of stationary-phase and acid-adapted *E. coli* O157:H7, *Salmonella,* and *Listeria monocytogenes* in fruit juices. *Journal of Food Protection, 64*, 315–320.

Miller, L. G., & Kaspar, C. W. (1994). *E. coli* O157:H7 acid tolerance and survival in apple cider. *Journal of Food Protection, 57*, 460–464.

Nikdel, S., Chen, C. S., Parish, M. E., MacKellar, D. G., & Friedrich, L. M. (1993). Pasteurization of citrus juice with microwave energy in a continuous-flow unit. *Journal of Agricultural and Food Chemistry, 41*, 2116–2119.

Palazoglu, T. K., & Sandeep, K. P. (2002a). Effect of holding tube configuration on the residence time distribution of multiple particles in helical tube flow. *Journal of Food Process Engineering, 25*, 337–350.

Palazoglu, T. K., & Sandeep, K. P. (2002b). Computational fluid dynamics modeling of fluid flow in helical tubes. *Journal of Food Process Engineering, 25*, 141–158.

Patankar, S. V., Pratap, V. S., & Spalding, D. B. (1974). Prediction of laminar flow and heat transfer in helically coiled pipes. *Journal of Fluid Mechanics, 62*, 539–551.

Rizvi, A.F., Goedeken, D.L., Steet, J.A., & Tong, C.H. (1994). The design of a multimode microwave oven for providing heating uniformity and reproducibility. *1994 Annual Institute of Food Technology Meeting,* Atlanta, GA, June 25–29, Abstract #23-1.

Roberts, J. S., & Gerard, K. A. (2004). Development and evaluation of microwave heating of apple mash as a pretreatment to pressing. *Journal of Food Process Engineering, 27*, 29–46.

Saravacos, G. D. (1970). Effect of temperature on viscosity of fruit juices and purees. *Journal of Food Science, 35*, 122–125.

Sandeep, K. P., & Puri, V. M. (2001). Aseptic processing of liquids and particulate foods. In J. Irudayaraj (Ed.), *Food processing operations modeling: Design and analysis* (pp. 37–81). New York: Marcel Dekker, Inc.

Splittstoesser, D. F., McLellan, M. R., & Churey, J. J. (1996). Heat resistance of *E. coli* O157:H7 in apple cider. *Journal of Food Protection, 59*, 226–229.

Tajchakavit, S., & Ramaswamy, H. S. (1995). Continuous-flow microwave heating of orange juice: Evidence of nonthermal effects. *Journal of Microwave Power and Electromagnetic Energy, 30*, 141–148.

Tajchakavit, S., & Ramaswamy, H. S. (1997a). Continuous-flow microwave inactivation kinetics of pectin methyl esterase in orange juice. *Journal of Food Processing and Preservation, 21*, 365–378.

Tajchakavit, S., & Ramaswamy, H. S. (1997b). Thermal vs. Microwave inactivation kinetics of pectin methylesterase in orange juice under batch mode heating conditions. *Lebensmittel-Wissenschaft und-Technologie, 30*, 85–93.

Tajchakavit, S., Ramaswamy, H. S., & Fustier, P. (1998). Enhanced destruction of spoilage microorganisms in apple juice during continuous flow microwave heating. *Food Research International, 31*, 713–722.

Tandon, K., Worobo, R. W., Churey, J. J., & Padilla-Zakour, O. I. (2003,). Storage quality of pasteurized and UV treated apple cider. *Journal of Food Processing and Preservation, 27*, 21–35.

Toledo, R.T. (Ed.), (1999). *Fundamentals of Food Process Engineering.* (2nd Ed.). Gaithersburg, MD: Aspen Publishing, Inc.

Villamiel, M., López-Fandiño, R., Corzo, N., Martínez-Castro, I., & Olano, A. (1996). Effects of continuous-flow microwave treatment on chemical and microbiological characteristics of milk. *Zeitsrift für Lebensmittel Untersuchung und Forschung, 202*, 15–18.